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Halophytes, Algae, and Bacteria Food and Fuel Feedstocks

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Summary

The constant demand for increased energy, freshwater, and food stresses our ability to meet these demands within reasonable cost and impact on climate change while sustaining quality of life. This environmental Triangle of Conflicts between energy, food, and water, while provoked by anthropogenic monetary and power struggles, can also be resolved through an anthropogenic paradigm shift in how we produce and use energy, water, and food. With world population (6.6 billion) projected to increase 40 percent in 40 to 60 yr, proper development of saline agriculture and aquaculture is required, as 43 percent of the Earth's landmass is arid or semi-arid and 97 percent of the Earth's water is seawater. Using diverse arid areas with a total size equivalent to the Sahara desert, 8.6×10^8 hectare, it is shown that

(1) Developing biomass to its theoretical limits with 230 W/m^2 daily solar incident radiation could produce 6 kQ/yr (1 quad (Q) = 10^{15} Btu), or 13 times the world energy consumption (World Q) in 2004 of approximately 446.4 Q.

(2) State-of-the-art CO_2 -force-fed algae systems with 10 percent useful product (2g/m^2 per day) could produce 24 percent of the World Q (year 2004). In theory, these ponds or ponds co-located with flue gas desulphurization (FGD) CO_2 recovery system power plants could produce well over 10 times that, or over 2.4 times World Q (2004).

(3) Low-maintenance, low-capital-cost halophyte agriculture could produce 7.1 Q/yr seed-oil petroleum equivalent (assuming no processing losses).

(4) Converting half of the halophyte cellulosic biomass to an oil could produce an additional 90.5 Q/yr petroleum equivalent (no processing losses).

(5) Biomass oils having nutritional values are best suited as food feedstocks, and the cellulosic material as both fuel and food feedstocks.

(6) It is important to return proper residue proportions to the soil to help maintain soil carbon and fertility. A goal would be terra preta soils while mitigating risks associated with biomass containment.

Entire community life cycle saline agriculture and aquaculture is being developed. Such communities could free up freshwater and arable land for food with an abundance of energy, favorably impacting the environmental Triangle of Conflicts (energy, food, and water) and reducing harmful emissions including particulates.

The consequences of inaction in controlling the Triangle of Conflicts with attendant emissions peaking and levels are shown to have graphic similarities to those found in the Permian and dinosaur periods—each of which led to mass extinction. We are now dealing with existential issues.

Introduction

Humanity is locked into an environmental Triangle of Conflicts between energy, food, and water (ref. 1) that is in dire need of resolution. Almost daily there is news about ever-increasing demands, starving people, threatened freshwater resources, climate change, and catastrophic storms all in various states of crisis. What is happening? What is driving all these problems?

Anthropogenic global climatic changes are being driven by energy demands, depletion of freshwater resources as well as atmospheric, soil, freshwater, and seawater pollution. There is increasing desertification. Also, sea levels are rising faster than anticipated and oceans are warming, which are threatening the release of methane (20 times worse than CO₂ as a greenhouse gas) that is currently stranded in hydrate form both in the ocean and permafrost regions (ref. 2). Current CO₂ levels and rate of increase mimic those for the Permian and dinosaur periods of mass extinction. Humanity must respond to such an existential matter because the consequences of inaction can be devastating, as noted in the appendix.

We are a planet in transition:

- (1) Our world population of 6.6 billion (B) (2007) is projected to increase 40 percent to over 9 B in 2050.
- (2) Feeding these people with conventional agriculture will require a 40-percent increase in Earth's arable land or equivalent productivity increases.
- (3) Developing countries are seeing major market growth, demanding unprecedented increases in energy, water, and food.
- (4) Aviation petroleum-based fuel consumption alone is anticipated to grow 4 percent per yr and in 5 yr will require 116 B gal/yr to meet that demand (approx. 95B gal/yr, 2007).
- (5) The world energy consumption (World Q) is projected to grow to 600 quad (Q).

The question humanity is asking or needs to be asking is, "is there a way, or ways, to provide for our food and energy needs, while conserving freshwater, and still have a positive benefit on global climate?" While it will require a paradigm shift in the way we use and invest in our natural resources, the short answer is, "Yes!"

Biomass¹ is one of the Earth's most abundant natural resources that directly addresses humanity's concerns over global resources for energy, food, and freshwater—the Triangle of Conflicts—and climatic changes.

Biomass and its processing involves multiple stages from planting to harvesting with competitive demands between the freshwater and agricultural resources used as food and those used for fuel. Some processed biomass is more suitable for human and animal foods and others for fuels such as biodiesel or alcohols. Nontoxic seed oils, for example, are more suitable as food, and the post-processing residuals as either animal foods or fuel feedstocks. Processed seed-oil residuals are often the more valuable of the products. Biomass not suitable for either human or animal food because of toxicity, high cellulose, or simply bad taste, are more suitable for fuels assuming toxicity and environmental issues are resolved. In either case, any unresolved issues regarding their toxicity and/or environmental harm—or that from products released either during their processing into fuel or combustion of the fuel—degrades economic value.

Adding to this competition are the stresses of climate change and demands upon our arable land areas that supply our food. These lands are at risk or are affected by salinity, which is caused by shallow or rising water tables, underground pumping, and other factors such as pollution by nondegradable materials. Considering that approximately 43 percent of the Earth's landmass is arid or semi-arid and 97 percent of the Earth's water is seawater, these vast natural resources should be properly utilized.

¹The term "biomass" is not restricted to mean plant matter converted to biofuels; rather, herein we will refer to biomass as the biological material produced from environmental carbon (e.g., CO₂), water, and nutrients via photosynthesis; that is, inorganic carbon is converted to organic carbon. Examples include sugarcane, soybeans, *Salicornia*, algae, and bacteria, where the primary product is juice, seed oils, or cellular oils; the secondary product, process residuals, can be cost-effective food or fuel sources; and the resultant cellulosic waste can be a fuel source or soil conditioner. Other biomass sources such as *Jatropha* (toxic) are nonfood sources, and the seed oils and cellulosic matter could be modified and be processed to fuel sources.

In light of this, we seek alternatives in plants that thrive in brackish and saltwater with the ability to survive in arid lands. The development and application of these plants (halophytes) become the primary focus. Herein we introduce some not-so-familiar halophytes and present a few of their benefits, cite a few research projects (including some on the alternatives algae and bacteria), and then set theoretical limits on biomass production followed by projections in terms of world energy demands. It is realized that the introduction of new biomass agriculture and aquaculture methods will entail control and containment risks (ref. 3). Based on diverse arid lands with a total size equivalent to the Sahara desert (8.6×10^8 ha, or 2.1×10^9 acres),² these projections show that halophyte agriculture³ and algae systems can provide for World Q.

It is also recognized there are costs required for a paradigm shift in the way mankind uses and invests in natural resources, and of course production does not come without cost. There are a multitude of cost metrics (ref. 5), however; thus the primary focus of this report will be biomass production, as it is considered bad form to emphasize cost over our planet's sick bed.

Halophytes

Halophytes are saltwater-tolerant plants. Among these many plants, three potential biomass candidates—an annual, a perennial, and a grass, respectively—include

(1) *Salicornia bigelovii* (fig. 1), a leafless annual salt-marsh plant with green jointed, succulent stems that is indigenous to the U.S. Southwest (ref. 6) and is cultivated along the Arabian Sea coasts of Pakistan and India on the margin of salt lakes and Sri Lanka (Celon) (ref. 7) and other parts of the world. Similar

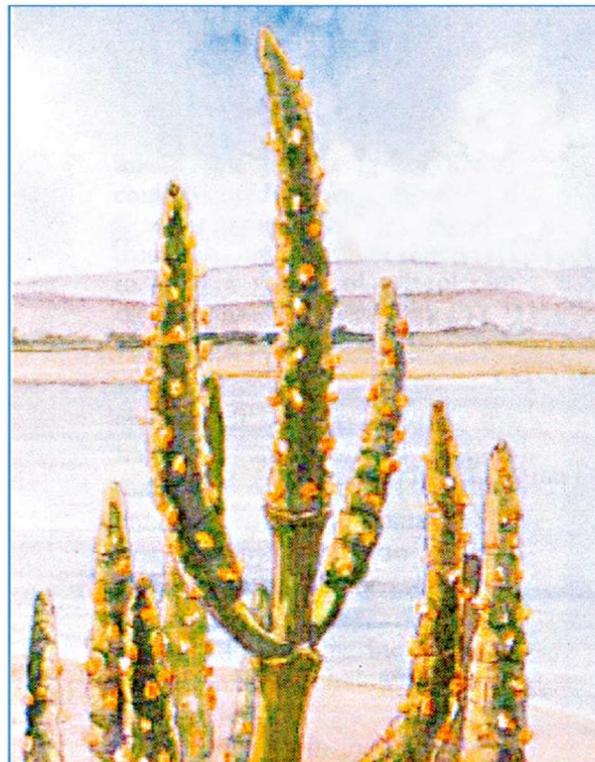


Figure 1.—*Salicornia bigelovii* (glasswort species).
From reference 6. Permission applied for, 1 Feb 2007.

²1 hectare (ha) = 2.471 acre, 1 ha = 10 000 m², and 1 km² = 100 ha.

³Many other saltwater-tolerant plant projects are supported through the International Center for Biosaline Agriculture (ref. 4).

TABLE I.—PERCENTAGE ACID CONTENT OF SEED OILS

[Taken from ref. 7a.]

Fatty acids	Salicornia bigelovii	Safflower	Soybean ^{a,b}	
			Commercial	Refined
C16:0 palmitic	7.52±0.24 (7.00 to 8.50)	6.70±0.25 (6.03 to 7.81)	11	11.76
C18:0 stearic	1.45±0.07 (1.24 to 1.69)	2.50±0.10 (2.05 to 3.00)	4.1	4.64
C18:1 oleic	13.42±0.56 (12.33 to 16.83)	12.30±0.70 (9.50 to 15.70)	22	24.98
C18:2 linoleic ω ⁶	75.50±2.04 (74.66 to 79.49)	78.00±3.50 (73.60 to 80.04)	54	55.41
C18:3 linolenic ω ³	1.98±0.09 (1.50 to 2.30)		7.5	3.8

^aReference 14, <http://chinese-school.net/firms.com/soybean-composition.html>, soybean commercial products.^bReference 15, http://www.scielo.br/scielo.php?pid=S0103-90162005000300014&script=sci_arttext, soybean refined oil.

Figure 2.—Seashore mallow flowering and setting seed (see refs. 16 and 17).

varieties have been developed and are grown by Hodges (ref. 8), Glenn (ref. 6), and Yensen (refs. 9 to 11) (see also refs. 1, 12, and 13). Hodges (Seawater Foundation, ref. 13) has several hundred hectares under development. The “fatty” acid (nutritional) values of three oils are addressed in table I, which shows, for example, *Salicornia* oil comparable to safflower oil, which is known to benefit cardiovascular health. However, large field trials with subsequent processing for *Salicornia* oils are currently lacking.

(2) Seashore mallow, *Kosteletzkya virginica* (KV), a perennial among the many saltwater-tolerant plants that grow in the wilds of coastal marshlands or inland brackish lakes (fig. 2). With the rise of sea levels due to glacial melt imperiling seashores, halophytes and saltwater algae are being looked upon as major sources of food and fuel feedstocks (ref. 1).

Schill (ref. 18) reports that a 2.5-acre developing test plot of seashore mallow produced 13 bu/acre of seed in a very dry season (fig. 3). The oil content of seashore mallow is also similar to that of soybeans (about 18 percent) with a fatty acid composition more like cottonseed. Seliskar and Gallagher (ref. 16) have presented a one-page summary of this work. The concept is to establish a carefree crop: enter the field once to plant or apply fertilizer and/or pre-emergent and once to harvest.

(3) *Distichlis spicata*, a halophyte grass (fig. 4). Halophyte grasses are being planted in response to saline-affected lands. In the year 2000, Australia had an estimated 5.7 million saline-affected hectares with potential to reach 17 million ha (170 000 km²) by 2050 (ref. 20).

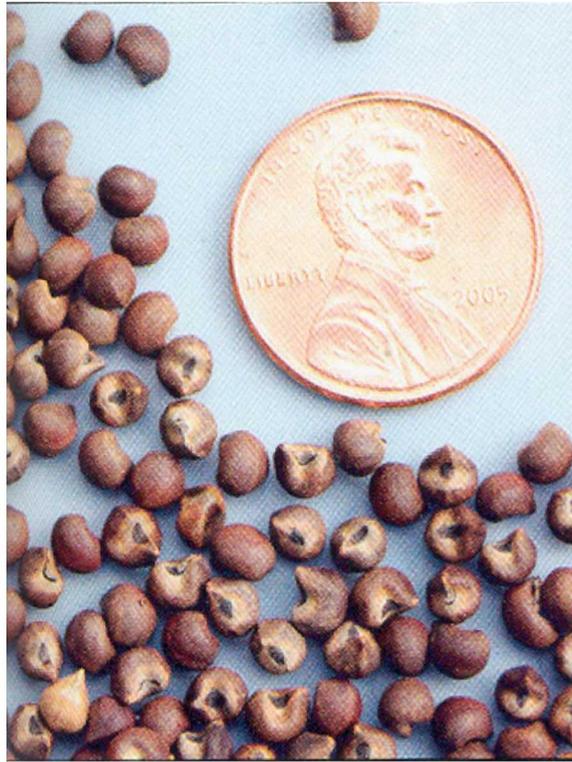


Figure 3.—Seashore mallow seeds (ref. 18; see also ref. 16).



Figure 4.—Halophyte grass *Distichlis spicata* (from ref. 19).

Distichlis spicata is most suited to the high temperatures and high-radiation regimes during the warm summer months of southern Australia (M.R. Sargeant, 2008, Department of Agricultural Sciences, La Trobe University, Bundoora, VIC 3086, Australia, private communication (see also ref. 21)). This species not only has the ability to grow and spread in saline waterlogged soils, but also produces valuable green feed in moist saline discharge soils during the summer period. Such forage has real value for mixed-farming biomass systems.

Arid-area halophytes are being studied as potential sources of biofuels that do not compete with agricultural resources devoted to food production (ref. 22; Amram Eshel (<http://www.tau.ac.il/~amram/>) and Yoav Waisel (waisel@post.tau.ac.il), 2007, Tel Aviv University, Israel, communications on Israeli halophytes; and Moshe Silberbush, 2007, Ben-Gurion University of the Negev, personal communication). In the deserts of the world, areas that are not currently under cultivation could become productive using saline or reclaimed water. Even the so-called second-generation plants—castor beans and *Jathropha*—will not grow well under arid conditions, yet over 50 t/ha/yr dry biomass has been achieved under desert conditions and reclaimed water irrigation. Until efficient methods for cellulose degradation are available, these could be used for earning Clean Development Mechanism (CDM) credits (ref. 23) by afforestation projects in developing countries and proper management of soil carbon and remediation practices (ref. 24). The low investment costs for halophyte production could mean that they would be ideal economically and agriculturally.

Algae Research

Realizing the availability of seawater and arid land, that “there is only 0.03 percent CO₂ in our (lower) atmosphere and on this thin thread hangs our very existence” (ref. 25), and that increasing that concentration also increases biomass productivity, we begin to force feed biomass to produce both food and fuel.

Mituya et al. (ref. 26) reported on a combustor gas generator pilot plant. The algae beds were CO₂-force-fed, covered-trough systems, citing 3.5 g/m²-day average biomass growth. In 1952, Arthur D. Little (ref. 27) reported on pilot plants and economics of biomass culture of algae systems where the algae were force fed bottled CO₂ mixed with air.

Force feeding usually requires co-location with a CO₂ source (e.g., a power plant, large-capacity CO₂ tanks, or pipelines). Further, whether open- or covered-pond or forced-fed systems, some algae are hardy, some are delicate, and some are better suited for food or specialized products. Delicate algae are not very tolerant to variations in their nutrient and CO₂ supply or their environment (e.g., temperature, salinity, density, mechanical stress, pH, etc.). Their yields and product quality can drop dramatically and are often wiped out by predators or other algal species. However, there are others that are hardy and can withstand these variations without much loss in yield and are more suitable for fuel production or that will permit more contaminants and less restraints in terms of food production.

Current algae issues are very nicely covered by Ben-Amotz (ref. 28, unpublished), who considered an operational algae plant and investigated processes and methods to reduce associated costs. Agreements between producers, processors, and marketers are plentiful; for example, [Inventurechem.com](http://www.venturechem.com) has a collaboration with Seambiotic Ltd. and the Israel Electric Corp. AlgaTech in Israel (ref. 29) and Earthrise Nutritionals LLC in Calipatria, California, U.S.A. (ref. 30), are commercial food suppliers with a large industry in Indonesia supplying food supplements to Japan.

A nonfood algae production analysis presented at the San Francisco Algal Summit (ref. 28, unpublished) shows a 50:1 cost reduction using CO₂ stackgas from FGD⁴-Power Station, Ashkelon, Israel (431 mt/hr CO₂, or 10 344 mt/day CO₂), with average mid-large station at 4000 mt/hr CO₂; algae raceway ponds were co-located with the power plant. In round numbers, 2 kg biomass requires 1 kg water and 3 kg CO₂ plus maybe up to 1 kg nitrogen (N) nutrient fertilizers (questionable). For complete capture and stoichiometric conversion, a natural-gas-fired powerplant producing 4000 mt/hr CO₂ has the potential to

⁴Flue gas desulfurization.

produce 2660 mt/hr biomass while consuming 1330 mt/hr water; this is equivalent to 16 000 mt biomass produced, using 7980 mt water and about 8000 mt N nutrients each day, assuming 6 hr/day of production and the 18 hr of excess CO₂ produced would require sequestration. Here, the need for higher cost phosphorous (P) is reduced, and the use of seawater would provide up to 80 percent of the essential nutrients.

The VertiGro system (ref. 31) and those of Rodolfi et al. (ref. 32) essentially turn a flat-surface greenhouse into a greenhouse with a series of vertical surfaces for biomass production. Flat or vertical-surface greenhouse systems are similar to the more common uniformly spaced horizontal or vertical tubular bioreactors where specialized biomass such as algae are used for food supplements or additives. One still requires ample sunlight, nutrients, contaminant control, and CO₂ as discussed by Dimitrov (ref. 33) for a similar scaleable modular photobioreactor system. Nevertheless, overcoming the light saturation effects (LSE) are to some extent aided by vertical greenhouse systems (ref. 34). (See also other algae sources; e.g., <http://www.algalbiomass.org/> and <http://www.nationalalgaeassociation.com/>.)

Bacteria Research

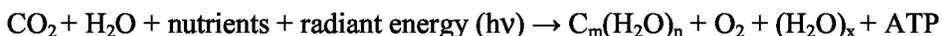
Cyanobacteria are some of the oldest bacterial forms known and are found in almost any habitat on Earth. The chloroplast, which enables plants and algae food production, facilitates an endosymbiotic relation between cyanobacteria living within plant or algae cells. The bacterial genomes are thus easier to modify than algae and higher plants. They can fix both nitrogen and carbon with energy obtained through photosynthesis (refs. 35 to 37).

Bacteria are prolific and reproduce rapidly. With proper conditioning in terms of nutrients, CO₂, and so forth, they can be harvested daily. Their maturation cycle corresponds to the solar day; however, night and cloud cover need to be properly addressed. Natural or modified bacteria can be used to absorb solar energy at different wavelengths, and some can tolerate extremes in temperature such as those found in the hot springs at Yellowstone National Park. Bacterial biomass have significant potential to achieve the 100 g/m²-day theoretical biomass limits set by Weismann (ref. 38) and discussed in the next section. The yield is quite significant, yet very challenging in terms of daily harvesting operations, scale-up to larger facilities, and biomass containment risks (ref. 39).

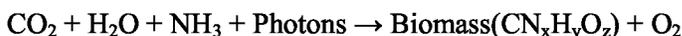
Theoretical Biomass Limits

The question now becomes, “just how much energy do plants collect from the Sun, and at what efficiency do they convert inorganic carbon to organic carbon?”

Plants produce carbohydrates through the metabolic process of photosynthesis, in which radiant energy is used to convert inorganic carbon into organic carbon (ref. 40):



or



where ATP is the nucleotide adenosinetriphosphate and assuming plants take in required nutrients (e.g., NO₃ and NH₃).

Plant photosynthesis occurs primarily in the visible spectrum (400 to 700 nm, with a dip near 600 nm (green)), which is about 45 percent of the incident solar spectrum called photosynthetically active radiation (PAR) (ref. 41). The average energy of a mole of PAR photons is 217 kJ.

Plants require 8 to 12 photons to fix one molecule of CO₂; one mole of fixed-CO₂-equivalent chemical biomass energy is 475 kJ. The theoretical photosynthetic efficiency (1) in terms of PAR is

22 percent or (2) in terms of total solar spectra, the photosynthetic efficiency is $22\% \times 45\% = 10\%$, with biomass production at $100 \text{ g/m}^2\text{-day}$ dry biomass (refs. 28 (unpublished) and 38).

Sugarcane is among the best solar energy-to-biomass converters with a photosynthetic efficiency of 2 percent producing up to $24 \text{ g/m}^2\text{-day}$ biomass compared with temperate-zone agriculture at 1/4 to 1 percent. Current halophyte efficiencies and production are similar to soybeans, and algae open-pond systems is 3.1 percent total solar at $20 \text{ g/m}^2\text{-day}$ dry biomass (see Table II).

TABLE II.—THEORETICAL AND CURRENT PRACTICE BIOMASS PRODUCTION AND CONVERSION EFFICIENCIES

	Conversion efficiency ^a	Yield ^a
Theoretical	PAR, 22 percent Total solar, 10 percent	$100 \text{ g-dry-biomass/m}^2\text{-day}$
Current practice		
Agricultural crops	Best: 2 percent total solar Normal: 0.3 percent	
Halophytes		Similar to soybeans (see below)
Algae (high solar zone)	3.1 percent total solar	$20 \text{ g-dry-biomass/m}^2\text{-day}$
Biomass food and fuel feedstocks ^b		
Palm oil production ^c		$1187 \text{ gal/ha-yr} = 3.25 \text{ gal/ha-day}^d$
Soybean oil production ^c		$150 \text{ gal/ha-yr} = 0.4 \text{ gal/ha-day}$
Algae oil production ^f		$4900 \text{ gal/ha-yr} = 13.4 \text{ gal/ha-day}$
Brazil ethanol		$1604 \text{ gal/ha-yr} = 4.4 \text{ gal-ethanol/ha-day}$

^aUseful conversion factors: $\text{m}^2/\text{ha} = 10^4$, $10^6 \text{ Btu} = 293.1 \text{ kWhr}$, $1 \text{ kcal/day} = 0.0484 \text{ W}$, $Q = 10^{15} \text{ Btu}$, and Heat Content: biodiesel = $1.26 \times 10^5 \text{ (Btu/gal)}$ and ethanol = $0.84 \times 10^5 \text{ (Btu/gal)}$.

^bOther seed oils. For oilseeds statistics, see reference 42:

- a. <http://www.fas.usda.gov/oilseeds/circular/2005/05-11/table4.pdf>
- b. <http://www.fas.usda.gov/oilseeds/circular/2005/05-11/table9.pdf>
- c. <http://www.fas.usda.gov/oilseeds/circular/2005/05-11/table10.pdf>
- d. <http://www.fas.usda.gov/oilseeds/circular/2005/05-11/table15.pdf>
- e. <http://www.fas.usda.gov/oilseeds/circular/2005/05-11/table19.pdf>

For tables of oilseed yields for variety of plants, see reference 43:

http://journeytoforever.org/biodiesel_yield.html.

For some fuel characteristics, see reference 44: <http://www.eere.energy.gov/afdc/pdfs/fueltable.pdf>.

^c 4 ton/ha-yr (0.89 to 0.92 gm/cm^3 , 3.44 kg/gal). See reference 42 (above), reference 45

<http://www.fas.usda.gov/pecad2/highlights/2004/08/maypalm/index.htm>, and reference 46

<http://www.chempro.in/palmoilproperties.htm>.

^dNot all available for biodiesel; for example, extract beta-carotene.

^eSee reference 47: <http://en.wikipedia.org/wiki/Biodiesel> and reference 48

<http://www.fapri.missouri.edu/outreach/publications/2006/biofuelconversions.pdf>.

^f23 percent conversion $20 \text{ g/m}^2\text{-day}$ biomass (ref. 28, unpublished).

Halophyte Agriculture and Algae Systems

Irrigating large tracts of desert land with saltwater can have one unintended anthropomorphic effect: namely, turning adjacent desert into farmland. The evaporating water from these planted tracts will change the local weather pattern, resulting in condensation, and change dry climates to wetter climates. This is the exact reverse of what is happening in large tracts of land next to the Sahara desert, where the desert soaks up the moisture and expands into the adjacent farmlands. Such an event has been a critical issue in Beijing for the last few decades. Because of rampant deforestation, the Gobi desert has been creeping towards Beijing for the last few decades, and persons returning after several decades have noted it is now much drier and sandier than it used to be. Putting large amounts of water into the desert for the water to vaporize can potentially make places like Beijing a little wetter and promote vegetation growth, which will in turn put more water in the atmosphere. Ultimately, it has the possibility of halting or outright reversing the desert expansion.

Fuel Versus Food: Adversary Feedstocks

The major issue is choosing between producing food or oil because there is a limited amount of arable land. That is why saline agriculture—an undeveloped source of both food and fuel—is so interesting. Saline agriculture, when combined with aquaculture, as accomplished in the Manzanar Project (ref. 49), Seawater Farms Eritrea, and Mexico Project (see refs. 12 and 13), provides food, fuel feedstocks, habitat, and redistribution of freshwater resources. Seawater irrigation requires a lot of water, around 4 ft/yr for each acre.

Yet seawater irrigation also provides about 80 percent of the nutrients needed for plant growth and requires only additions of phosphorous, iron, and nitrogen, suggesting the need for genetically modified nitrogen-fixing halophytes (ref. 50). Soybeans and alfalfa are good arable-crop (glycophyte) nitrogen-fixing food and fuel feedstocks; if those same characteristics can be developed in halophytes and combined with aquaculture, as in tilapia farming, we are on the road to both food and feedstocks for oil independence. However it is important to combine these efforts with meteorology and global climate modeling to ensure that redistribution of seawater to arid and semi-arid regions (terra forming) provides a favorable climate balance and avoids adverse and unintentional consequences, such as anthropogenic global warming (ref. 50).

The point is that through research in diverse plant development and processing, engineered to produce higher yields and more efficient use of these oils,⁵ biofuel feedstocks could provide a larger and larger portion of the transportation fuel demand. For food production, for example, Bushnell (ref. 50) cites cases of genomic-derived halophyte tomatoes, eggplant, rice, wheat, and rapeseed, which appear to be quite successful. Also, irrigation agriculture is diverse, and has produced a large portion of fruits, nuts, and vegetables and also contributing to forage, fiber, industrial (paper, rubber, resins, solvents, and others), medicine, and ornamental products (ref. 51). When it is combined with aquaculture, such as fish or shrimp farming, there are benefits to both in terms of long-term sustained production (refs. 17, 52, and 53).

Fuel-Food Feedstock and Freshwater Possibilities

Consider the possibilities of producing food and fuel feedstocks while conserving freshwater:⁶ Since 43 to 44 percent of the Earth landmass is arid or semi-arid, there is the potential for developing a multiplicity of seawater-irrigated regions to produce halophyte crops and combine them with aquaculture. Now suppose that the size of these diverse, multiple regions is that of the Sahara desert (ref. 56), 8.6×10^8 ha, and these diverse regions produce 100 bbl/ha-yr of bio-oil (bbl is barrel): The total equivalent energy produced would be 421.4 Q, or 94 percent of the 2004 World Q (ref. 55).

Developing biomass to its theoretical limits with total solar incident radiation at 230 W/m^2 daily on various arid areas with a total size of the Sahara desert (8.6×10^8 ha, 13.6 percent of world arid or semi-arid lands) could produce 5.92 kQ/yr, or 13 times the World Q (2004).⁷

For this same arid (desert) area, current state-of-the-art, CO_2 -force-fed open-pond algae systems with 10 percent usefuel biomass ($2 \text{ g/m}^2\text{-day}$) product can produce 106 Q/yr of petroleum equivalent, which is 24 percent of the World Q (2004). This production volume is also equivalent to 37 percent of the world liquid fuel consumption (2004), two-thirds (approx. 24 percent) of which is considered to be

⁵For cost effectiveness, the nontoxic byproducts (e.g., nutrients used as ruminant animal food) can be significantly more important than the seed oils.

⁶Earth land size $148.9 \times 10^6 \text{ km}^2$ ($148.9 \times 10^8 \text{ ha}$), 29.2 percent of its surface (ref. 54). The size of the Sahara desert is $8.6 \times 10^6 \text{ km}^2$ ($8.6 \times 10^8 \text{ ha}$), envelopes nearly all of Northern Africa, and is about the same size as the total U.S. landmass ($9.2 \times 10^6 \text{ km}^2$, or $9.2 \times 10^8 \text{ ha}$). A barrel (bbl) of oil equivalent to a barrel of bio-oil, corrected for energy content to No. 2 diesel, is $5.4 \times 10^6 \text{ Btu/bbl} \times 0.91$ (bio-oil to oil equivalent conversion) = $4.9 \times 10^6 \text{ Btu/bbl}$ of bio-oil. If bio-oil production were 100 bbl/ha-yr, then total energy produced would be $(8.6 \times 100 \times 4.9) \times 10^{14} = 42.14 \times 10^{16} \text{ Btu} = 421.4 \times 10^{15} \text{ Btu} = 421.4 \text{ Q}$. World energy consumption (ref. 55) (year 2004) = 446.4 Q. United States energy consumption = 98 to 99 Q. Note 1 bbl = 42 gal.

⁷Average high-incident solar radiation is 230 W/m^2 daily. At 10 percent maximum photosynthetic conversion, this becomes 0.552 kWhr daily and $6.88 \times 10^9 \text{ Btu/ha-yr}$ or $6.88 \times 10^{-6} \text{ Q/ha-yr}$. Thus, 8.6×10^8 diverse assorted hectares could produce 5.92 kQ/yr or 13 times the World Q (2004).



Figure 5.—Model of seawater ecological community (ref. 8).

transportation fueling (ref. 57). In 2004, the world transportation industry used 20 to 25 percent of the World Q (ref. 58), in good agreement with the (approx. 24 percent) cited prior (assumes no processing losses). In laboratory and pilot experiments, CO₂-force-fed algae ponds produce 10 times that much biomass (20 g/m²-day), or 2.4 times the World Q (2004); whether, laboratory, pilot, or scale-up, each requires co-location with sustainable sources of CO₂, water, nutrients, and sunlight.

Again using this same arid area, low-maintenance and low-capital-cost halophyte agriculture could produce 7.1 Q/yr of seed-oil petroleum equivalent. Converting half of the cellulosic biomass to an oil would produce an additional 90.5 Q/yr petroleum equivalent (assumes no processing losses). The oils having nutritional value are best suited as food, and the cellulosic material as both fuel and food feedstocks.⁵

It is important to return a proper proportion of the processing residuals to the soil to help maintain soil carbon (see terra preta soils, ref. 24), as long as any potential pathogens are monitored and controlled.

Halophyte agriculture is low maintenance and a low-capital investment. Entire community halophyte agriculture/aquaculture, as proposed for example by Hodges et al. (ref. 8) (fig. 5)⁸ could free up freshwater supply and arable lands for food production while reducing ocean rise ingress onto arable land. Freeing up freshwater with its abundance of energy and food dramatically impacts the Triangle of Conflicts—energy, water, and food—which are the resources that spawn conflicts (even fighting) among people and nations.

Supposing that the production, logistics, and political issues could be overcome, the total energy from such arid land sources scattered over the Earth would be sufficient to meet the world's energy demands (refs. 60 and 61). As such, if humanity chose, and if we became committed, it could be accomplished.

⁸An enhanced picture of saline agriculture/energy production. Currently the majority of the world's energy production comes from a few countries. However, the move to energy production from halophytes, algae, bacteria, and solar photovoltaic, solar thermal, drilled geothermal, and wind has the potential to distribute energy production more evenly over diverse areas throughout the world. It could also play a big role in the Green Revolution that is currently occurring in Africa and other parts of the world. Imagine the impacts on communities within Africa alone; if they had the potential to produce and export energy for the world. This would provide many regions with the means to feed themselves and raise their standard of living. It also provides future investment for the Middle-East countries, as well as the Americas and others, that currently produce a lot of our petroleum-based energy—providing them with a future income stream when the current reserves of fossil fuels diminish and eventually run out. These countries have large tracts of desert and arid lands with access to plentiful saline water (both groundwater and ocean water). Another aspect is that there are other benefits such as environmental (e.g., effects of sea level rise), which are delineated for example by Sargeant (ref. 59) and Hodges (ref. 8). Also re-vegetating areas would provide new habitat for wildlife. There would be so many spinoffs, including social and environmental ones that would also be brought along if we were to move in the direction of saline energy production (ref. 8 and M.R. Sargeant, 2008, Department of Agricultural Sciences, La Trobe University, Bundoora, VIC 3086, Australia, private communication.).

Conclusions

The stresses of climate change and the demands upon arable land areas that supply our food and freshwater resources are incompatible with our demands for transportation fueling. These lands are at risk or affected by salinity, which is caused by shallow or rising water tables, underground pumping, and other factors such as pollution by nondegradable materials.

1. Humanity is locked into an environmental Triangle of Conflicts between energy, food, and water provoked by anthropogenic global climatic changes and is questioning if there is a resolution. While it will require a paradigm shift in the way we use and invest in our natural resources, the short answer is, Yes!

2. The world population, 6.6 billion (B) is projected to increase 40 percent in 40 to 60 years and will demand energy, freshwater, and food. Within the next 5 years, aviation fueling alone will increase from an estimated 95 B gal/yr (2007) to 116 B gal/yr while world energy consumption (World Q, 1 quad (Q) = 10^{15} Btu) demand grows to 600 Q. With such increases in energy, food, and freshwater demands, how are we to meet them?

3. These demands can be met by properly using the Earth's vast resources for saline agriculture and aquaculture; 43 percent of the Earth's landmass is arid or semi-arid, and 97 percent of the Earth's water is seawater. To illustrate the use of saline agriculture, an arid area comprising diverse, multiple regions totaling the size of the Sahara desert, 8.6×10^8 ha, is used:

a. Developing biomass to its theoretical limits with average solar incidence at 230 W/m^2 daily could produce 5.92 kQ/yr, or 13 times World Q (year 2004).

b. State-of-the-art algae systems with 10 percent useful product ($2 \text{ g/m}^2\text{-day}$) could produce 106 Q/yr petroleum equivalent, which is 24 percent of the World Q. This production volume is also equivalent to 37 percent of the world liquid fuel consumption (2004), two-thirds of which is considered to be transportation fueling. In 2004, the world transportation industry used 20 to 25 percent of the World Q (assuming no processing losses).

In theory, both algae ponds force fed with CO_2 from tanks and those co-located with power plants (e.g., coal fired) equipped with flue gas desulphurization (FGD) CO_2 -recovery systems can each produce over 10 times that much ($>20 \text{ g/m}^2\text{-day}$), or nearly 2.4 times the World Q (2004).

c. Low maintenance, low-capital-cost halophyte agriculture could produce 7.1 Q/yr seed-oil petroleum equivalent. Converting half of the cellulosic biomass to an oil would produce an additional 90.5 Q/yr petroleum equivalent (assuming no processing losses).

d. The oil nutritional values are best suited as food and the cellulosic material as fuel and food feedstocks. The potential for any residuals to be animal or fish feedstocks depend on their nutrient value and toxicity.

e. It is important to return proper proportions of residue to the soil to help maintain soil carbon and fertility with pathogen control; a goal would be terra preta soils with very low biomass containment risk.

4. Entire community saline agriculture and aquaculture as being developed presently could free up freshwater and arable lands for food with an abundance of energy, which drastically impacts the environmental Triangle of Conflicts (energy, water, and food), which are the resources that spawn conflicts (even fighting) among people and nations.

5. Emissions peaking and levels have graphic similarities to those found in the Permian and dinosaur periods—each of which led to mass extinction. We are now dealing with existential issues, and the consequences of inaction in controlling the environmental Triangle of Conflicts can be severe.

Appendix—Consequences of Inaction (Elements of Mass Extinction)

Humanity is locked into an environmental Triangle of Conflicts between energy, food, and freshwater (ref. 1) that is crying out for resolution, and we must deal with its associated problems (including harmful emissions CO₂, NO_x, ultrafines, etc.). Almost daily we hear about ever-increasing energy costs, desertification, starving people, threatened freshwater resources, climate change, uncontrolled emissions, and catastrophic storms all in various states of crisis. What is happening? What is driving all these problems?

As of 2008, and in the near future, it appears that the power-generation and transportation industries will be heavily dependent on hydrocarbon-based fuels, with transportation based heavily on petroleum fueling. These industries, while the keys to economic strength, have engendered a multiplicity of problems centered on the environmental Triangle of Conflicts between energy, food, and water that requires resolution for survival of humanity. Industrial and transportation combustion cycle heat engines generate CO₂, particulates (ultrafines), and of course heat. Ultrafines present serious pulmonary (ref. 62) and vascular (ref. 63) human health hazards and are likely to also affect living matter in general. One action being taken to reduce the production of ultrafines is through the use of dimethylether (DME) as a fuel or fuel-blend (ref. 64) since DME fueling diminishes both NO_x and ultrafines (particulates). Excessive anthropogenic CO₂ and the rate at which CO₂ is being generated has been implemented in climate change models and found to be largely responsible for current climate changes and those yet to be felt. The introduction and blending of biomass industrial and transportation fueling will reduce both the level and the rate of CO₂ release yet still support combustion cycle heat engines.

We now want to investigate the consequences of inaction in decreasing our reliance on conventional hydrocarbon-based fueling.

Recent uncontrolled anthropogenic CO₂ levels and peaking rates are shown to be similar to those found in the Permian and dinosaur periods each of which led to mass extinction. The latter were natural events, and the former stem from abuses within the environmental Triangle of Conflicts. We are now dealing with existential issues.

While theories and popular notions abound as to how dinosaurs vanished 65 million years ago (Mya), their pursuit incubated searches that have enabled construction of an increasingly refined timeline of the Earth spanning over 400 000 yr. The two largest Earth mass extinctions are dated to the Paleozoic era (Old life) beginning 530 Mya and ending with mass extinction 250 Mya (Permian period), followed by Mesozoic era (Middle life) ending with mass extinction 65 Mya (when the dinosaurs became extinct), followed by Cenozoic era (New life) to present day and the potential of an impending anthropogenic-engendered mass extinction.

To explain such an event as mass extinction, the Alvarez group (see ref. 65) and most of the scientific community settled upon asteroid/meteorite/comet impact displacing large amounts of debris into the atmosphere obliterating incident solar radiation, plunging the planet into darkness and a near lifeless, cold prolonged winter. Still, a few others pursued an unpopular, often belittled, position that changes in thermochemical balances of the Earth's oceans and atmosphere trigger such events. Similar theories are applied to the great extinction at the end of the Permian period, where 90 percent of the life on Earth is believed to have vanished.

Resolving these polarized positions has required timeline refinements, massive amounts of geological data, and a significant boost from computational modeling. The emerging timeline shows many extinction events with a general increase in diversification of species (ref. 65).

To construct the timeline, isotope techniques applied to core and rock samples provided initial metrics to characterize the climate at specific times. The photosynthesis-based meter relied on the ¹²C:¹³C ratio, providing evidence exploited by both groups. The isotope ¹²C is the isotope of choice of plant photosynthesis, leaving ¹³C in the atmospheric CO₂ reservoir; some marine species, such as shell-forming clams, use either isotope, and rapid decay of isotope ¹⁴C dates events to 80 000 yr. The geothermal-based meter relies on the ¹⁶O:¹⁸O ratio, noting that less ¹⁸O is taken up in mineral trappings during warmer periods. Chromatographic techniques have refined and sharpened the Earth's climatic timeline.

Geological data reveal changes in the Earth's magnum spilling out over large regions forming basalts, such as the Siberian Traps (see ref. 65) with massive CO₂ release. Other data show changes in ocean thermal- and salt-concentration-driven currents with changes in the thermocline (and halocline) and oxygen stratification, leading to deep-water anoxia that supports sulfur-loving bacteria; these changes are also affected by the Earth's plates and orbit and of course, the Sun.

Life forms are held in a delicate balanced coupling between incident solar flux involving van Alan belts, ozone and atmospheric layer shields, magnum, the core, and the Earth's oceans, which constitute nearly 71 percent (ref. 66) of its surface, providing heat, mass, and chemical exchange. Data show that changes in Earth's ocean currents, shift of plates, and volcanic and basalt formations altered this delicate balance. It is to these changes caused by global warming—with ocean O₂ loss due to CO₂ acidification and anoxic oceans spawning H₂S and CH₄ releases coupled with massive basalt and volcanic CO₂ release (Siberian Traps)—that we attribute the 90 percent extinction rate of the Permian period 250 Mya and the dinosaurs 65 Mya with an estimated 60 percent extinction rate.

As such, it is to these data (including that of the Permian period) and past extinction events that we draw the parallels with current natural and anthropogenic effects on our planet and our own existence (see table III). The key factors seem to be BOTH the level (now nearing 400 ppm) and the rate of change of CO₂ in the atmosphere.

TABLE III.—EFFECTS OF CO₂ ON EARTH DURING PERMIAN PERIOD COMPARED WITH CURRENT TRENDS

Permian period, approximately 60 million years ago (CO ₂ from Permian Siberian volcanoes)	Current (Human activities generate over 100 times that CO ₂)
Fossil data indicates CO ₂ warming.	GREATLY accelerating and amplifying warming. Balanced cooling effects from volcanic debris and SO ₂ .
Fossil methane released.	22 times worse than CO ₂ for warming, coming from tundra and oceans (immense amounts sequestered).
Fossil CO ₂ released.	Fossil CO ₂ release and release from anthropogenic activities.
Warming oceans and increased ocean acidification reduces algae growth and promotes O ₂ decline and anoxia.	Global ocean warming and increased ocean acidification reduce CO ₂ uptake, resulting in O ₂ decline and anoxia (e.g., Black Sea bottom).
Ice melting due to albedo changes and warming.	Faster ice melting, resulting in albedo changes.
Atmospheric water (assumed) leads to increased atmospheric temperatures.	Water evaporates and is THE warming gas, leading to increased atmospheric temperatures (some 12 to 14 °C by 2100). At these temperatures, ALL the ice melts (beyond 2100); oceans rise 80 m, destroying homes of 2.5 billion people and engendering plate movements and volcanic activities.
Ocean circulators stop.	Temperature and saline differences drive ocean circulators, which largely disappear; circulation slows, changes directions, or stops.
Oceans go anoxic, promoting anoxic bacteria that love sulfur and produce H ₂ S.	Happening NOW, losing a chunk of ocean equal in size to state of Texas each year to anoxic conditions. Anoxic bacteria produce H ₂ S; warmth causes sporadic release of CH ₄ hydrates.
CH ₄ and H ₂ S releases destroy ozone layer and make atmosphere toxic. Estimated 90 percent extinction.	CH ₄ and H ₂ S releases destroy ozone layer and make atmosphere toxic. Acid rain destroys plant, animal, and human life as now known. Potential 95 percent species extinction.
	IF all of the methane and CO ₂ are released from the oceans, then we become VENUS: Harsh climate of Venus is a result of greenhouse effect from volcanic activity with CO ₂ release.

Volcanic CO₂ and SO₂

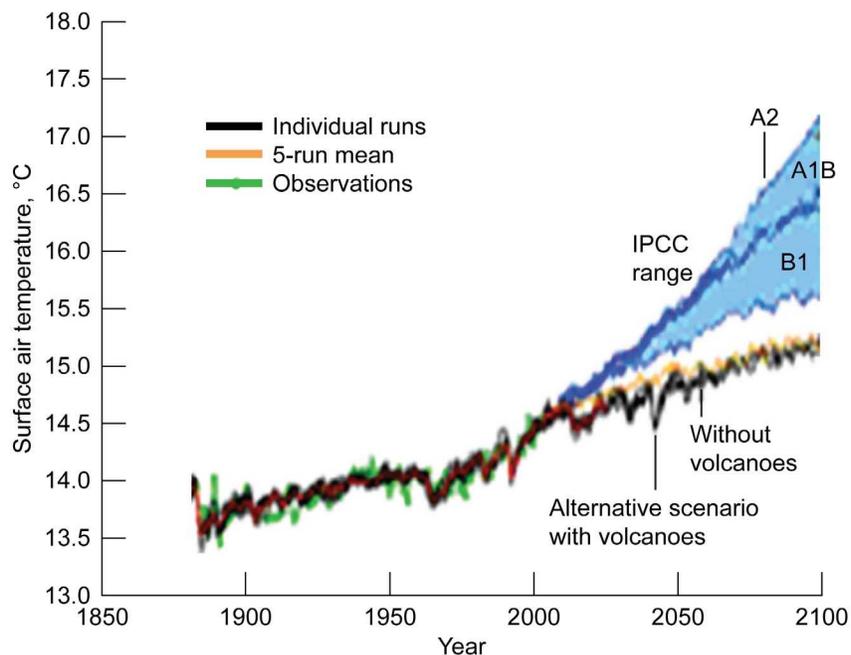
Estimates place volcanic CO₂ release at 130 to 180 B (billion) kg/yr (ref. 67), but anthropogenic CO₂ emissions are on the order of 150 times larger. Other estimates place volcanism at 500 B kg/yr, which when combined with natural biomass cycles, places the atmospheric CO₂ reservoir near 2.2×10¹⁵ kg. Our current land use and fossil fuel consumption produce a net of 17.6×10¹² kg/yr that has progressively increased that CO₂ reservoir estimate to 2.69×10¹⁵ kg (refs. 68 to 70).

The 1970 to 1977 time-averaged subaerial volcanic SO₂ emissions flux is 13 B kg/yr (13×10¹² g/yr); 4 B kg from eruptions and 9 B kg from passive degassing (ref. 71). Total natural sulfur release is about 24 B kg/yr with anthropogenic contribution at 79 B kg/yr mostly in the Northern Hemisphere (ref. 71).

Warming Problems

The consequences of present-day warming climatic changes and rapid rise of CO₂ as occurred in the Permian extinction affect human health and result in an increase in tropical diseases (e.g., malaria), the loss of birds with an increase of insects, storm mortality, sea-level rises, starvation, a decline in grain production and increase in tropical fruit and starches among many others, and serious rapid population growth with threats of warfare (nuclear) and outright colonization. Over 2000 years ago the Sahara was the breadbasket of the Roman Empire; now it is a desert as a result of climate change. Based on informed predictions, it becomes imperative that CO₂ plateau at 450 ppm for survival as we know it (ref. 65), but most likely will level off near 800 ppm with massive destruction before humanity will do anything about it. Battisti (ref. 72 and cited pp. 194 to 199 in ref. 65) thinks it will be worse and peak at 1100 ppm, and he provides a ghostly description of the new world. In addition, Battisti feels that climate models based on the Eocene epoch (warming period beginning 60 Mya and ending 33 Mya with no ice left at the poles, see extinction map, ref. 73) are inadequate to apply to this century—the extent of extinction of living species cannot be surmised. Ward adds his own three scenarios (pp. 200 to 204, ref. 65), which parallel the scenarios of Battisti and those of Hansen (2005, 2006, and fig. 6).

Hansen’s model (refs. 74 and 75) shows “business as usual” (upper locus, fig. 6), which according to Ward (ref. 65) and Battisti (ref. 72) leads to mass extinction. Hansen’s alternative scenario leads to



Intergovernmental Panel on Climate Change (IPCC) scenarios (from ref. 2):

A2: represents heterogeneous world with regional development similar to “business as usual.”

A1B: represents improved but balanced utilization of fossil and nonfossil energy sources.

B1: represents world population peaks midcentury then declines with rapid change toward a service and information economy with clean, efficient technologies.

Alternative scenarios represents additional CO₂ forcing of ~1.5 W/m² by 2100.

Figure 6.—Twenty-first century global warming outcomes from Hansen’s model (ref. 74).

benign-warming at less than 1 °C (lower locus, fig. 6). Hendricks (ref. 2), considering methane fuels and methane release from methane hydrates, also warns if that climate thermal changes follow Hansen's upper locus in figure 6, it is questionable if humanity or other living matter can survive, as none can convert methane gas to oxygen. Planetary life is headed for extinction; meanwhile we continue to argue legality of our planet's fragile state even to the Supreme Court (ref. 76). The Battisti et al. Supreme Court Brief also cites the detrimental effects of unabated greenhouse gas release (primarily CO₂, CH₄, N₂O, and fluorocarbons) and notes that time is critical in acting upon their reduction.

Climate Control

Seawater and CO₂ levels are rising as occurred in the Permian and other periods, but this time it is due to anthropogenic effects. Engineering approaches to anthropogenically control the climate have been suggested to reverse these risings.

Crutzen (ref. 77) proposed to alter Earth albedo by burning S₂ or H₂S in the stratosphere that converts to SO₂ sub-micrometer sulfate particles. As our planetary ecological system is in such a delicate balance, these types of climate control measures appear too dangerous to implement.

There are too many unknowns, given that small changes can have large irreversible effects on that balance. This is also acknowledged by Crutzen who states that albedo enhancement should only be used when proven advantageous and when humanity commits, with all diligence, to support the reduction of greenhouse gases; he is not optimistic the support will be there, however, noting that global military expenditures, for example, are approaching US\$1000 billion (nearly half by the United States alone).

The Seawater Foundation approach to climate control is the use of arid and marginal lands and seawater rivers, in a complete life cycle, producing food-fuel feedstocks while conserving freshwater—an approach not considered by Crutzen. The approach is also anthropogenic but offers an effective countermeasure to the Permian scenario of general warming with rapid CO₂ rise and impending mass extinction. It also affords an enhancement in biodiversity in contrast to recent trends toward specialized food sources, which virtually eliminate biodiversity.

A continuation of discussions and a summary of climate change problems is provided by Meinshausen et al. (ref. 78).

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14. ABSTRACT The constant, increasing demand for energy, freshwater, and food stresses our ability to meet these demands within reasonable cost and impact on climate while sustaining quality of life. This environmental Triangle of Conflicts between energy, food, and water--while provoked by anthropogenic monetary and power struggles--can be resolved through an anthropogenic paradigm shift in how we produce and use energy, water, and food. With world population (6.6 billion) projected to increase 40 percent in 40 to 60 yr, proper development of saline agriculture and aquaculture is required, as 43 percent of the Earth's landmass is arid or semi-arid and 97 percent of the Earth's water is seawater. In light of this, we seek fuel alternatives in plants that thrive in brackish and saltwater with the ability to survive in arid lands. The development and application of these plants (halophytes) become the primary focus. Herein we introduce some not-so-familiar halophytes and present a few of their benefits, cite a few research projects (including some on the alternatives algae and bacteria), and then set theoretical limits on biomass production followed by projections in terms of world energy demands. Based on diverse arid lands with a total size equivalent to the Sahara Desert (8.6'108 ha, or 2.1'109 acres), these projections show that halophyte agriculture and algae systems can provide for the projected world energy demand.					
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